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Structure and mechanical properties of mechanically alloyed Al/Al-Cu-Fe composites

S. D. KALOSHKIN, V. V. TCHERDYNTSEV*, A. I. LAPTEV
Moscow State Institute of Steel and Alloy, Leninsky prosp. 4, Moscow, 119049, Russia
E-mail: vvch@misis.ru

A. A. STEPASHKIN
State Scientific and Research Institute of Graphite-Based Structural Materials, Electrodnaya ul. 2, Moscow, Russia

E. A. AFONINA, A. L. POMADCHIK
Moscow State Institute of Steel and Alloy, Leninsky prosp. 4, Moscow, 119049, Russia

V. I. BUGAKOV
L. F. Vereshchagin Institute for High-Pressure Physics RAS, 142190, Troitsk, Moscow Region, Russia

Quasicrystalline (QC) powder was prepared by mechanical alloying and subsequent annealing of $Al_{65}Cu_{23}Fe_{12}$ composition. Obtained quasicrystals were milled together with pure aluminium in the ratios of Al-20 wt% QC and Al-10 wt% QC. A hot consolidation of samples was performed under pressure of 4.5 GPa at elevated temperatures. X-ray diffraction study of the as-consolidated samples shows that the quasicrystalline phase remained in the samples if consolidation temperature was lower than 500°C. Consolidation at higher temperatures results in disappearing of the QC and formation of crystalline phases, such as Al_2Cu and Al_7Cu_2Fe by reaction between QC and aluminium matrix. SEM study of microstructure of the composite alloys shows an absence of open porosity in the consolidated bulk samples. Besides rather large particles of reinforcing phase of about 20 μm there are also very small particles of less than 1 μm. The uniformity of particles distribution in the matrix increases with increase in the milling duration. Microhadrness measurements and compression tests were performed, an effect of the treatment parameters on the compressive strength was studied.

1. Introduction

Recently, the ball-milling technique is widely used for producing the metal-matrix composite materials [1–7]. The mixing of matrix and filling materials at ball-milling proceeds in the solid phases, which can help to keep the useful properties of filling particles in case of their low thermal stability. Other advantage of this technique is the performing of supervised mechanochemical reaction, resulting in the composites formation, directly in the mill [4, 5]. Furthermore, the ball-milling allows to obtain materials with micro- and nanocrystalline structure, which can improve the mechanical properties of composites.

In recent years, quasicrystalline (QC) phases, due to a unique complex of properties, have attracted much attention as promising base for new materials [8–10]. The peculiarities of the electron configuration of QC phases cause their unusual properties, which may be useful for industrial application. The most important are the mechanical properties, such as high strength (9–11 and even 13 GPa have been reported [11] in comparison with 7–8 GPa for martensitic steels), hardness and wear resistance. Young's modulus of quasicrystals was measured to be 100–200 MPa. Hardness of Al-Cu-Fe quasicrystals is about 10% of the Young's modulus, which is close to the ratio obtained for diamonds and some ceramics. Increase in temperature results in significant decrease in quasicrystal's hardness [12].

QC phases possess high antifriction properties, because they are very hard and, simultaneously, have very low friction coefficient. Such low friction coefficient is caused by low surface energy of QC: 28 mJ/m^2 [13]. For instance, the surface energy of most slippery fluorocarbon polymer is 18 mJ/m^2, of Al_2O_3 monocrystal – 47 mJ/m^2, of water – 72 mJ/m^2, the surface energy of pure metals make up several hundreds mJ/m^2. This fact indicate that interatomic bonds of QC are highly saturated even in the surface layers; consequently, QC surface is expected to be chemically inert, that could cause a high corrosion resistance of these phases.

*Author to whom all correspondence should be addressed.

High brittleness and, consequently, low deformability are the main disadvantages of QC phase as material for industrial application in bulk shape. In some studies, QC were suggested to be used as surface coating in friction details due to their antifriction properties [14] and also in solar absorbers due to their special optical properties [15].

At the same time, quasicrystals look very perspective as a reinforcing phase for composite materials. QC were suggested as a filling phase for Al matrix [16], also QC-filled maraging steel was developed for surgical application [17]. In some papers producing of Al/QC composite using the ball-milling technique was reported; quasicrystals of Al-Cu-Cr [18], Al-Cu-Fe [19, 20] and Al-Mn-Ce [20] systems were used as reinforcing phases.

In our papers [21–25], we reported the method for Al-Cu-Fe QC single-phase powder producing using mechanical alloying (MA) of pure elements and subsequent annealing. Recently we applied the ball-milling technique to produce Al/Al-Cu-Fe composites, the phase and structural transformation in the composite powders were studied [26, 27]. In present paper we report the first obtained results on the bulk composite samples preparation and investigation of their mechanical properties.

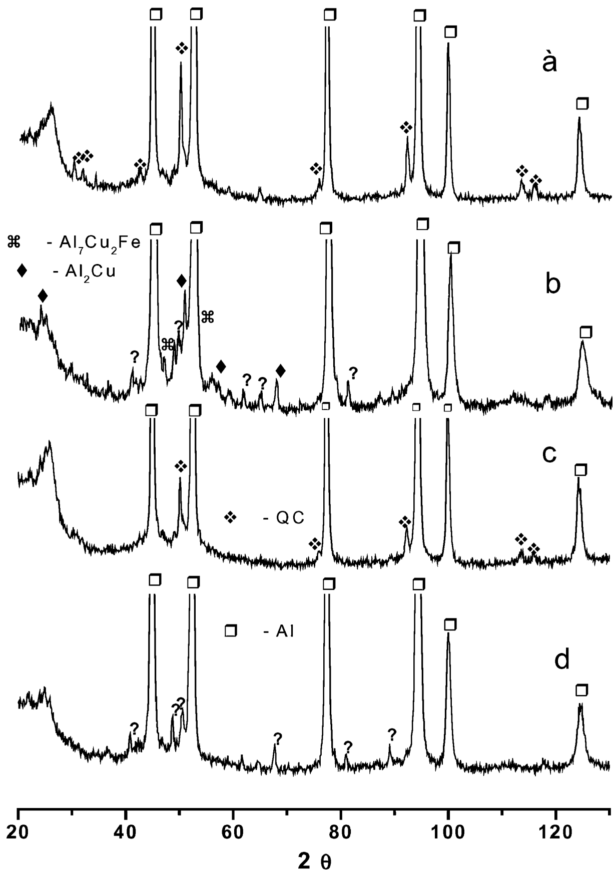

Figure 1 X-ray diffraction patterns for the consolidated samples: (a) Al + 20 wt% QC, 300°C, (b) Al + 20 wt% QC, 600°C, (c) Al + 10 wt% QC, 300°C, and (d) Al + 10 wt% QC, 600°C.

2. Experimental procedure

Powders of carbonyl iron (99.95%) annealed in hydrogen, copper (99.9%) and aluminium (99.0%) were used for the experiments. MAPF-1 planetary ball mill with two vials (volume 1000 cm^3 each) of hardened carbon-chromium steel, running at a vial rotation velocity of 600 rpm was employed for composite preparation. Balls of 9 mm in diameter were used, with a ball-to-powder mass ratio of 10:1. MA was performed in Ar atmosphere. A DRON-3 diffractometer with Co-K_α radiation was used for X-ray diffraction (XRD) experiments. The phase composition was determined by the reduced Rietveld method, i.e., by fitting to the full experimental X-ray powder diffraction patterns.

CamScan scanning electron microscope (SEM) was used to investigate the microstructure of samples. Consolidation of powder into bulk samples of 4 mm in diameter was performed under the pressure of 4.5 GPa at various temperatures with ageing for 10 s or 5 min. Microhardness of the consolidated samples was measured by Vickers indentation using a PMT-3 machine with a tetrahedral diamond pyramid, applying the load during 5 s. Compression tests were performing using Zwick 1474 machine.

3. Results and discussion

The samples of $Al_{65}Cu_{23}Fe_{12}$ composition were prepared by milling of elemental powders during 1 h. To obtain the single-phase icosahedral quasicrystalline structure, this powder was annealed in Ar atmosphere for 1 h at 800°C. The quasicrystal preparation was described in detail in our previous papers [21–25]. To produce the composite, this quasicrystalline powder with size fraction 20–60 μm was milled together with the Al powder in the ratios of Al-20 wt% QC and Al-10 wt% QC. Milling duration was varied from 5 to 60 min.

Fig. 1 shows the X-ray diffraction patterns of the consolidated samples. For the samples, consolidated at 300°C, besides the patterns from the Al matrix, only the peaks of the QC phase present in the spectra. As well as in the case of the powder samples [26, 27], heating up to 300°C at consolidation results in the keeping of the phase composition of sample is the same that of the as-milled samples. Consolidation at 600°C results in disappearing of the QC diffraction peaks and formation of the crystalline phases. In addition to Al_7Cu_2Fe phase, also a significant amount of Al_2Cu phase and the phase with unknown structure formed at heating.

Fig. 2 shows the microstructure of the composite samples. No pores can be found in the structure. One can see that in addition to rather large particles of reinforcing phase of about 20 μm there are also very small particles of less than 1 μm. An increase in the milling time probably makes the distribution of particles in matrix more uniform.

Fig. 3a shows the dependencies of microhardness on the temperature of consolidation for Al-10 wt% QC composite. Increase in the milling time results in the significant increase in microhardness magnitude. No difference in microhardness with temperature was observed for the samples milled for 10 min—up to 300°C and for the samples, milled for 30 min—up to 500°C. At temperatures higher than 500°C, weak decrease in microhardness was observed for both milling times. For

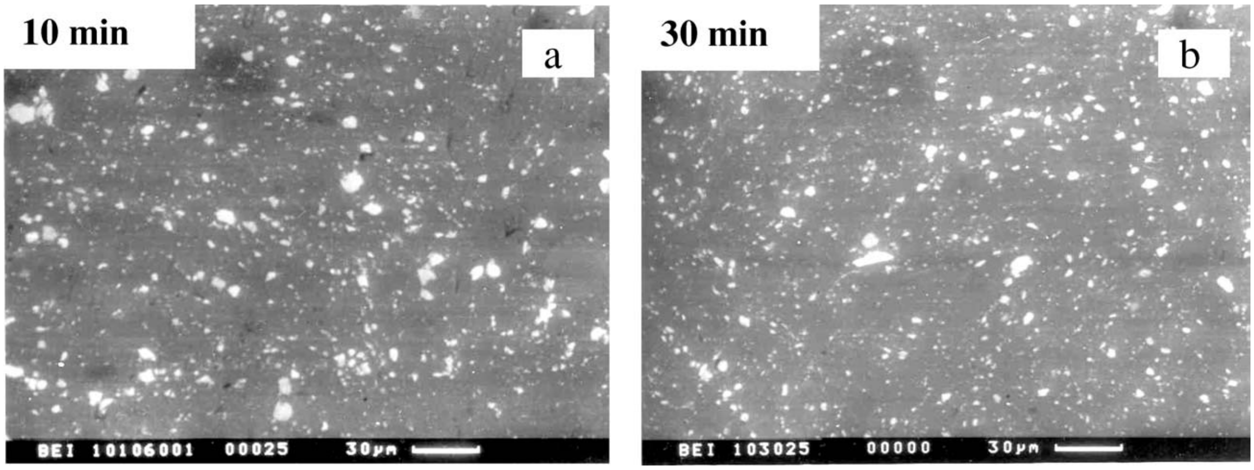

Figure 2 SEM micrographs of Al-10 wt% QC consolidated samples, milled for (a) 10 and (b) 30 min. Dark fields correspond to Al matrix, light fields correspond to QC reinforcers.

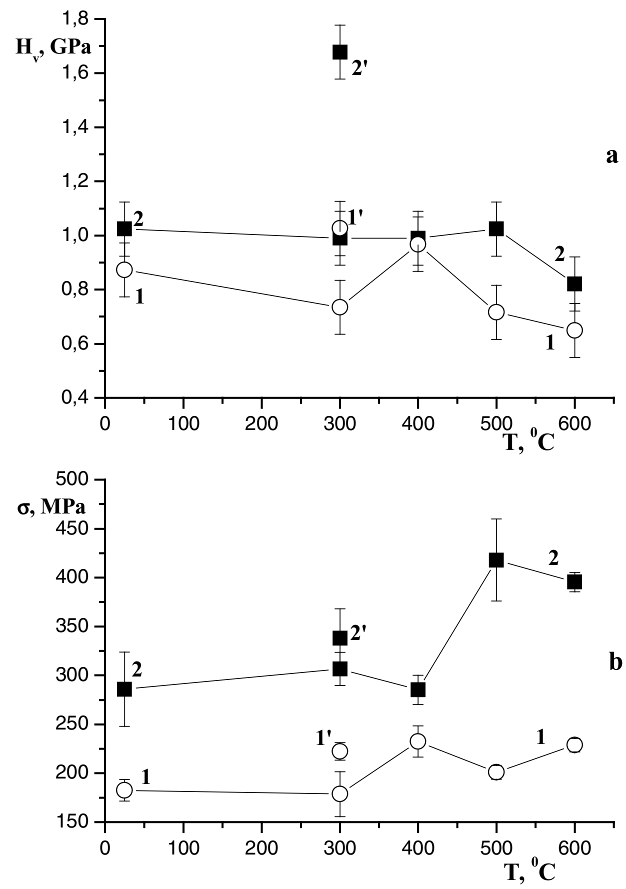

Figure 3 Dependencies of (a) microhardness H_V and (b) compression strength σ of Al-10 wt% QC composite on the consolidation temperature. (1, 1′) – 10 min of milling; (2, 2′) – 30 (a) and 60 (b) min of milling; (1, 2) – ageing for 10 s; (1′, 2′) – ageing for 5 min.

samples, consolidated at 300°C, the effect of ageing under pressure on the mechanical properties was studied. As it is shown in Fig 3a, the increase in ageing time results in significant increment of microhardness.

Compression experiments show that crushing of samples proceeds by formation of the extensive cracks in the direction of applied loading. Fig. 3b shows the dependences of compression strength σ on the consolidation temperature. As well as it was observed for microhardness, increase in milling time results in significant increasing in σ. Also increase in time of ageing under pressure results in increase of the measured magnitude. Values of σ change insignificantly with the consolidation temperature up to 300–400°C, at higher temperatures an appreciable increase in σ was observed for both used milling time.

Comparing the results of the investigation of mechanical properties with the data of phase analysis, presented in this paper and in [26, 27], we noticed that the change in mechanical properties at elevated temperatures is associated with the change in phase composition of the samples. Also the increase in the grain size, which has to occur at high-temperature treatment, may play a role in changes in mechanical properties.

4. Conclusions

Al-based composite materials reinforced by quasicrystals were prepared. The MA technique was used for preparation of precursor powder of QC phase from elemental powders and for aluminium based composite preparation. Hot high-pressure consolidation of powders was applied for producing bulk composite samples with compact structure, no visible pores were observed in the micrographs. The temperature stability of the composites is not high, an increase in the temperature results in the interaction of quasicrystalline phase with aluminium matrix yielding formation of other crystalline phases. This transformation is accompanied with increase in microhardness and decrease in the compressive strength.

Acknowledgements

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